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TORSION TESTING OF ALUMINUM AT HIGH RATES OF STRAIN

THEODORE NICHOLAS

and

GEORGE F. GAREY

Major, USAF

TECHNICAL REPORT AFML-TR-69-172

JULY 1969

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FOREWORD

This report was prepared by the Strength and Dynamics Branch, Metals and Ceramics Division, under Project Number 7351, "Metallic Materials", Task Number 735106, "Behavior of Metals". The research work was carried out at the Air Force Materials Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Ohio, by Dr. T. Nicholas of the Strength and Dynamics Branch and Maj. G. F. Garey of the Air Force Institute of Technology.

This report covers work performed from September 1967 to April 1969 and is based, in part, on a thesis submitted by Maj. Garey in partial fulfillment of the requirements for the degree of Master of Science at the Air Force Institute of Technology, Wright-Patterson AFB, Ohio.

The manuscript was released by the authors May 1969 for publication.

This technical report has been reviewed and is approved.

W. J. Trapp

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ABSTRACT

A machine for testing hollow cylindrical specimens in torsion at shear strain rates up to 10/sec is described. A differential capacitor is incorporated in the circuitry to produce a voltage signal proportional to angle of twist of the specimen. Experimental results are presented for four grades of aluminum in shear over a range in strain rates from 10^{-5} to 10/sec. The data show no strain-rate sensitivity in 7075-T6 and 2024-T4 aluminum and only slight rate sensitivity in 1100-0 and 1199-0 aluminum. Comparisons with results of other investigators show good agreement.

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I. INTRODUCTION

The mechanical properties of materials under dynamic loading conditions is a subject of both theoretical and practical significance that has attracted the interest of many investigators in recent years. One result of this wide interest has been the generation of large amounts of experimental data and the development of new and sophisticated experimental testing techniques at high rates of strain. The state-of-the-art in dynamic plasticity has been well documented in the recent book by Cristescu [Ref 1]. A survey of mechanical properties of materials at high rates of strain has been compiled by Lindholm [Ref 2] and a review of several aspects of dynamic behavior of materials is contained in the survey article by Nicholas [Ref 3]. Examination of these and other references reveals that a divergence of views still exists on the effect of strain rate on the mechanical properties of metals. An examination of the data generated over the last 40 years reveals quantitative, as well as qualitative differences for the same solids, even for similar experimental configurations [Ref 4]. Most of the attention has been focused on the properties of materials under uniaxial (assumed, at least) stress states in tension and compression. In addition to plastic wave propagation studies in long rods and tensile tests utilizing high speed testing machines, the split Hopkinson pressure bar technique developed by Kolsky [Ref 5] has received increasing popularity as a tool for generating data on materials properties at high rates of strain. However, the unresolved question of the effects of neglecting radial motion and the averaging of stresses in this latter technique has produced a lack of complete confidence in this test. Furthermore, the necessity of assuming, a priori, a stress-strain relationship in inelastic wave propagation experiments has made it difficult, if not impossible, to interpret these results in terms of a unique constitutive equation for the material. Finally, the tensile test suffers the shortcomings of both necking at large strains and the neglect of wave propagation phenomena in the interpretation of experimental data. There is thus still a shortage of good experimental data on the effect of strain rate on the mechanical properties of materials.

Concurrently, a number of investigators have been studying materials properties in a state of uniaxial strain using plate on plate impacts. These experiments while eliminating many of the difficulties associated with uniaxial stress experiments, are confined to extremely high stresses producing nearly hydrostatic stress states and involve large elastic strains of the order of the plastic strains. They are used mainly to provide information on the pressure-density relation or equation of state of materials. Shear or strength effects are often neglected in these studies. The strain-rates involved in these experiments are extremely high and are associated with the rise times of shock waves in the materials.

A search of the literature reveals very little information on the dynamic properties of materials in torsion. One reason for this obviously is the lack of experimental facilities capable of deforming a material in pure torsion at high loading rates or of producing torsional waves in hollow tubes. One notable exception to this is the work of Baker and Yew [Ref 6] involving their experiments on copper. Their studies involved the propagation of torsional plastic waves in long, thin-walled hollow tubes and a setup analogous to a split Hopkinson pressure bar in torsion instead of compression. They noted a significantly lower strain rate sensitivity in shear in copper than had previously been reported in tension or compression. Additional studies using this technique were conducted by Yen and Yew [Ref 7] on iron. Previous to this, a limited number of investigations involving torsion to study strain-rate effects in metals had been conducted [Ref 8, 9, 10, 11]. However, these investigations were limited to rather low strain rates and, in most cases, lacked the versatility of determining constant strain rate response over a wide range of strain rates.

In addition to the lack of data on materials in torsion, there still remains a large void in the data on dynamic materials properties. One area which is particularly lacking is in the intermediate strain rate region (0.1 - 100/sec) at rates slower than obtainable with split Hopkinson bar or plate impact type tests yet higher than test speeds achievable on conventional testing machines. To help fill this data gap, a high speed torsion testing machine has been developed through modifications of a machine previously used to test polymers at high speeds at Columbia University.

The torsional mode of deformation was chosen for this investigation because of its inherent advantages; the dependence of the displacements on a single space variable in a thin-walled tube, the existence of only one non-zero component of stress and strain with no three dimensional effects complicating the interpretation of results, the lack of changes of geometry during the test, and a deformation which involves only deviatoric stress and strain with no volumetric changes.

It is to be noted that only the deviatoric stress and strain components are associated with plastic deformation in the theory of plasticity. The assumption of incompressible plastic flow in metals except at very high pressures has been confirmed by the experimental observations of Bridgman [Ref 12]. Also, time-dependent behavior in viscoelastic materials is usually associated with the deviatoric stresses and strains, the relation between dilatational stress and strain usually being assumed to be elastic and time-independent. It was thus felt that most could be learned from this type of experiment involving only shear stress and strain regarding fundamental materials properties and strain rate effects.

This report presents a description of the apparatus and procedures used for testing materials in pure torsion over a wide

range of shear strain rates from 10^{-5} up to 10/sec. In addition, some experimental data on several aluminum alloys are presented for comparison with those of other investigators.

II. DESCRIPTION OF APPARATUS

The apparatus shown in Figure 1 with a specimen in place is essentially a pneumatic device which applies an eccentric load to a cylinder supported on bearings in a rigid housing. Compressed nitrogen gas is stored in a 115 cu. in. reservoir and can be released by cutting off the electric current to a solenoid actuated valve. The release of the valve provides nearly instantaneous application of full pressure and drives a 3" diameter piston which in turn applies the eccentric load through a 5" lever arm to the steel barrel supported by roller bearings in a rigid housing. The velocities attained depend upon the pressure of the stored gas, the strength of the test specimen, and the inertia of the system. For the specimens of aluminum shown in Figure 2 and for a pressure of 100 psi the maximum attainable shear strain rates were approximately 10/sec.

In addition to its function as a dynamic testing machine, the apparatus can be used to perform quasi-static tests by driving a 5" lever arm linked to a block on a jackscrew at the other end of the machine as shown in Figure 3. The jackscrew can be powered through reduction gears by an electric motor and thus provides a convenient method of performing quasi-static torsion tests or applying a slow pre-twist to the specimen before testing dynamically. The static and dynamic test modes operate independently at opposite ends of the machine and can thus be used individually or simultaneously to superimpose a dynamic torque on a quasi-statically applied torque without any unloading occurring.

The torque is measured by a load cell composed of a torsional strain gage bridge on a cylinder between the specimen and the jackscrew or static loading end of the machine. The strain gage bridge is composed of eight 120 ohm gages mounted in 4 pairs on opposite sides of the cylinder and wired in series to cancel bending effects. The bridge is equivalent to a 4 arm active bridge of 240 ohm gages and is powered by a 12 volt d.c. power supply from a Honeywell Visicorder strain-gage conditioning preamplifier. The strain gage bridge output is fed through the signal conditioning preamplifier and then to either an oscilloscope or X-Y or strip-chart recorder and provides a signal voltage which is linearly proportional to torque.

For the tests involving the two soft aluminums (1100 and 1199), the amplifier output was too low and an additional amplifier had to be incorporated into the circuitry to give adequate gain for the recording instruments. Because of the extremely high gain on a very small output signal, a significant amount of electrical noise was introduced in the signal. This noise was significantly reduced by passing the signal through a 5000 Hz 12 db/oct. low-pass filter.

To measure the angle of twist of the specimen several techniques were considered. Although high-speed optical techniques

would appear to be the most direct, they suffer the handicap of requiring sophisticated and expensive equipment and involve rather complicated data reduction procedures. In addition, optical measurements for dynamic testing require high speed recording cameras. Mechanical methods which are good for static testing are inappropriate for dynamic tests in most cases because of inertia effects of levers, etc. and the associated difficulties of recording at fast speeds. Strain gages placed directly on a specimen are probably the most direct and accurate method of recording dynamic strains but are limited to the measurement of very small strains. The instrumentation finally decided upon was a differential capacitor coupled to a probe of a Decker Delta Unit, Model 902-1, a commercial device which converts small changes in capacitance into large analogous output voltages. The differential capacitor with a range from 8-20 μμf could be connected directly to either grip of the torsion machine through steel rods and provided changes in capacitance which were linearly proportional to the angle of twist of the grips of the specimen.

The specimen consisted of a thin-walled hollow tube (see Figure 2) having a wall thickness of 0.040" and an inner diameter of 0.500". It was determined that the thickness was thin enough to reasonably assume uniform shear stresses and thick enough to prevent any buckling. The gage length of the specimen was 1.9". The specimen was held in place by grips consisting of steel blocks with a hole the size of the specimen shoulder using 8 set screws in each grip to hold the specimen firmly in place.

III. EXPERIMENTAL TECHNIQUE

Four grades of aluminum were chosen to demonstrate the capability of the machine and to study strain-rate effects in torsion in two structural grades and two commercially pure grades. The structural grades were 7075-T6 and 2024-T4 while the pure grades were 1100-0 and 1199-0 which are 99.0 and 99.99% pure aluminum respectively. The content of the materials is summarized in Table 1. The specimens were machined from 1" diameter bar stock to the dimensions shown in Figure 2 prior to heat treatment. The two pure aluminums were annealed at 650°F for 1 hour followed by furnace cooling while the structural alloys were heat treated to the standard T6 and T4 conditions.

The load cell was calibrated by connecting a long lever arm to one grip of the machine and applying known weights while recording the strain gage bridge output simultaneously. The weights were added in equal increments up to the maximum torque expected and then unloaded in the same increments. The calibration of voltage output versus torque was found to be linear and exhibited negligible hysteresis effects due to friction in the system. The angular measuring device was calibrated by fixing a mirror to a rigid specimen and observing the image of a meter stick through a telescope with a fixed cross-hair. The rotation of the grip caused a simultaneous rotation of the differential capacitor through the connecting shaft. The output of the Decker Delta Unit was measured with a digital voltmeter and calibrated against the mirror-telescope measurements. The voltage output due to the change in capacitance was found to be linearly proportional to the angle of twist of the differential capacitor within 1% over a range of nearly 150° rotation. The total angle of rotation used in the experiments was only 17°.

To insure the most accurate results, the calibration procedures were repeated at regular intervals during the period of performance of the tests. In addition, the electronics remained on during the entire test period to minimize warmup drift. Variations in line voltage were eliminated by feeding the power to all instruments through a constant voltage transformer. Finally, the frequency response of the measuring apparatus was checked and ascertained to be sufficient for the maximum speeds encountered in these tests.

At least two specimens of each material were tested in the quasi-static configuration at each of three different speeds of rotation corresponding to shear strain rates of 10^{-5}, 10^{-4}, and 10^{-3}/sec. Two different speed motors and a speed reducer were used to obtain the three different strain rates. The output of the load cell and the differential capacitor and Decker Delta Unit combination were recorded on a Honeywell Visicorder and were converted to stress and strain versus time plots. The strain

rate was determined from the slope of the strain-time plot. In addition, the two voltage outputs were fed simultaneously to an x-y plotter in order to directly obtain a stress-strain curve.

Having completed the quasi-static tests and determined the stress-strain curve at each of three constant strain rates for each material, a series of dynamic tests was performed. A very small pretwist was applied to each specimen to remove slack from the system and then the dynamic torque was applied by releasing the solenoid actuated valve. The outputs corresponding to load and angle of twist were recorded on two channels of the Honeywell Visicorder operating at its maximum chart speed of 80 ips. In addition, timing marks from a Tektronix Time-Mark Generator were recorded on a third channel to provide a calibrated time base. The load and angle of twist outputs were also recorded simultaneously on an oscilloscope in the x-y mode, thereby producing a dynamic stress-strain curve in torsion. The shear strain-rate obtained in these tests was approximately 10/sec. and remained nearly constant throughout the test except at the very start because of inertia in the system. The entire test took less than 10 milliseconds. A complete schematic of the test-setup and the instrumentation used is presented in Figure 4.

Several preliminary tests involving dynamic loading superimposed on a quasi-statically applied pretwist were performed on the pure aluminums. These tests are discussed in the last section of this paper

IV. RESULTS AND DISCUSSIONS

The data for torque and angle of twist were converted to values of shear stress and strain using the well known elementary strength of materials formulas

$$\tau = \frac{Tr}{J} \qquad \gamma = \phi \frac{r}{\ell} \tag{1}$$

where r was taken as the mean radius of the thin-walled tube and ℓ the gage length of the specimen which was 1.9 inches. The error between the mean value of strain using the above formula and the actual values at the outer and inner radius of the specimens used in this investigation was 7.4 percent. The percent error for stress is approximately the same since the curvature of the stress-strain curves was small for all materials tested.

Data from several different tests were used to plot the final curves at each strain rate. The variations from test to test were below 5 percent in nearly all cases. When larger variations occurred, additional tests were conducted to obtain a better statistical average of the data. In many cases, the variations from test to test were greater than the variations from one strain rate to another. This was especially true for the 7075-T6 and 2024-T4 aluminum alloys and to a lesser degree for the pure aluminums. These variations from test to test occurred in spite of the fact that for each material the specimens were all machined from the same bar and heat treated in the same batch. Average stress-strain curves were obtained for each of the four materials at each of four approximately constant strain-rates comprised of three slow rates and one fast rate. The curves are presented as Figures 5 through 8 and show results up to four percent shear strain. It can be seen from Figures 5 and 6 that the two structural aluminum alloys, 2024-T4 and 7075-T6 are essentially insensitive to strain-rate in the range $\dot{\gamma} = 10^{-5}$ to $\dot{\gamma} = 10/\text{sec}$ within the accuracy of the experiments. Data points from the test at 10^{-4}/sec have been omitted for clarity but coincided with the curve drawn in each case.

Assuming a von Mises loading function and flow rule torsion test results may be compared to tension-compression tests by means of the invariants:

$$J_2' = -\left(\frac{1}{3}\sigma^2 + \tau^2\right)$$
$$I_2' = -\frac{1}{4}\left(3\epsilon_p^2 + \gamma_p^2\right) \tag{2}$$

Data from torsion tests are thus comparable to uniaxial stress-strain data if τ is replaced by $\sqrt{3}\,\tau$ and γ by $\gamma/\sqrt{3}$. If the elastic strains are negligible with rsspect to the total strains, then the comparison between tension-compression and

torsion data is equivalent whether the total strain or plastic strain is used. Data from the tests on 7075-T6 aluminum were converted to equivalent uniaxial tension data by this method and compared with the tensile data of Holt, et al [Ref 13] in Figure 9. The curve shows that a) the tension-compression and torsion data points agree quite closely and b) 7075-T6 aluminum is insensitive to strain rate over a wide range of strain rates from 10^{-3} to 10^{3} /sec. [see also Ref 14]. It should be noted that the present tests covered only a limited range of strains up to 4% in shear which is equivalent to 2.3% in tension or compression.

The results for the 2024-T4 aluminum, which also indicate a lack of strain-rate sensitivity, are in agreement with those of Hoge [Ref 15] who found no rate sensitivity in tension tests covering a range of strain rates from 10^{-5} to 20/sec. The 1100-0 and 1199-0 aluminum data presented in Figures 7 and 8 show a slight increase in flow stress with increasing strain rate. At four percent shear strain, the flow stress increases slightly less than 10% in the 1100-0 aluminum from the "quasi-static" value at $\dot{\gamma} = 10^{-5}$/sec to the dynamic value at $\dot{\gamma} = 10$/sec, i.e. over 6 decades of strain rate. For corresponding values of strain and strain-rate the flow stress increase in the 1199-0 aluminum is approximately 25-30%. This observed percentage increase in flow stress with increasing purity in aluminum confirms a trend previously noted by other investigators [Ref 13]. No comparison is presented here of the data for 1100-0 aluminum with tension-compression data of other investigators because of the limited range of strains covered in these experiments.

The data for the 1199-0 aluminum were replotted as flow stress against log strain rate for constant values of strain (Figure 10). It can be seen from this plot that a constitutive equation for this aluminum can be represented as a first approximation in the form

$$\begin{aligned} \tau &= \tau_0(\gamma) + C \log(\dot{\gamma}/\dot{\gamma}_0) \qquad & \dot{\gamma} > \dot{\gamma}_0 \\ \tau &= \tau_0(\gamma) & \dot{\gamma} < \dot{\gamma}_0 \end{aligned} \tag{3}$$

as suggested by Holt, et al [Ref #13] for all 0-temper aluminum alloys. For the 1199-0 studied here, $\dot{\gamma}_0$ would appear to be around 10^{-4}/sec. since there was no observable difference between the flow stresses observed at 10^{-5} and 10^{-4}/sec. Holt found $\dot{\varepsilon}_0$ in compression to be in the range 0.1 to 1.0 in/in/sec. It appears from the data that the strain rate sensitivity increases with increasing strain, thus the constant C in eq. 3 should be replaced by a function of strain as suggested by Lindholm [Ref 16], i.e.

$$\tau = \tau_0(\gamma) + \tau_1(\gamma) \log \frac{\dot{\gamma}}{\dot{\gamma}_0} \tag{4}$$

This increasing strain rate sensitivity with increasing strain is consistent with the observations of Lindholm for copper, aluminum, and lead [see also Ref 2] but the data here are insufficient to determine accurate numerical values for the functions or constants in eq. 4.

V. CONCLUSIONS

The experimental techniques and instrumentation employed in this investigation proved adequate to determine the stress-strain curves in shear for materials at nearly constant strain-rates ranging from 10^{-5} to 10/sec. The equipment cannot, however, provide data in the range between 10^{-2} and 10/sec strain rates in the present configuration. The maximum strain-rates could be increased by decreasing the gage length and/or increasing the radius of the specimen. This would also enable one to obtain higher maximum shear strains in a given test. The present geometry of the specimen limited the investigation to shear strains less than 5 percent. Several modifications are being performed on the equipment at present to increase the versatility of the testing system. These will be the subject of future reports.

The strain-rate sensitivity of two structural grades of aluminum, 2024-T4 and 7075-T6 is negligible in shear at strain rates below 10/sec. Pure aluminum does exhibit a slight strain-rate sensitivity which appears to increase with strain and increases with higher purity. However, the variation in flow stress of less than 10% for 1100-0 aluminum raises some serious questions as to the use of this material by a large number of investigators to study the strain-rate sensitivity of materials. It is the opinion of the authors that other materials should be used in experimental investigations in dynamic plasticity where the question of rate-sensitivity is of paramount interest. It is not surprising to find conclusions in the literature ranging from "strain-rate insensitive" to "strain-rate sensitive" to "representable by a single dynamic stress-strain curve" when characterizing the behavior of 1100-0 aluminum in high strain-rate or plastic wave propagation experiments. Experiments dealing with titanium or steel are suggested for future studies of strain-rate sensitivity in metals and will be the subject of forthcoming reports. In addition, the effects of strain history and strain-rate history on the mechanical behavior of metals at high strain rates is another question which must be answered before realistic constitutive equations for these materials can be developed. Recent studies by Klepaczko [Ref 17] have shown that strain-rate history has an important effect on the flow stress in pure aluminums and should be considered when studying the strain-rate sensitivity of metals.

Several preliminary tests at variable loading rates were conducted in this investigation on the pure aluminum. These tests involved loading the specimens at a very slow rate ($\dot{\gamma} = 10^{-5}$/sec) and then superimposing a dynamic torque equivalent to $\dot{\gamma} = 10$/sec. The resulting dynamic curve for the prestrained specimens coincided with the original dynamic curves for the annealed material within experimental accuracy. However, the electrical noise produced an accuracy which was no better than the magnitude of the variations of flow stress with strain rate

and obscured any loading history effects in the material. Again, the small rate sensitivity of the aluminum prevented a definitive description of the true nature of strain rate effects in metals and the use of more rate sensitive materials is suggested for future studies.

It appears that strain-rate may not necessarily be the important independent variable in the study of dynamic behavior of materials but, rather, plays the role of a convenient parameter in studies of this kind. It is thus suggested that variable strain and strain-rate history be included as an important feature in future studies and that investigators not confine their attention solely to constant strain rate testing.

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Table I

Specifications of Aluminum Alloys

Alloy	Nominal Compositions (%)					Minimum Aluminum (%)	Heat Treatment After Machining
	Copper	Manganese	Magnesium	Chromium	Zinc		
2024-T4	4.5	.6	1.5	---	---	---	T4
7075-T6	1.6	---	2.5	.3	5.6	---	T6
1100-0	---	---	---	---	---	99.00	1 hr at 650°F-Furnace Cooled
1199-0	---	---	---	---	---	99.99	1 hr at 650°F-Furnace Cooled

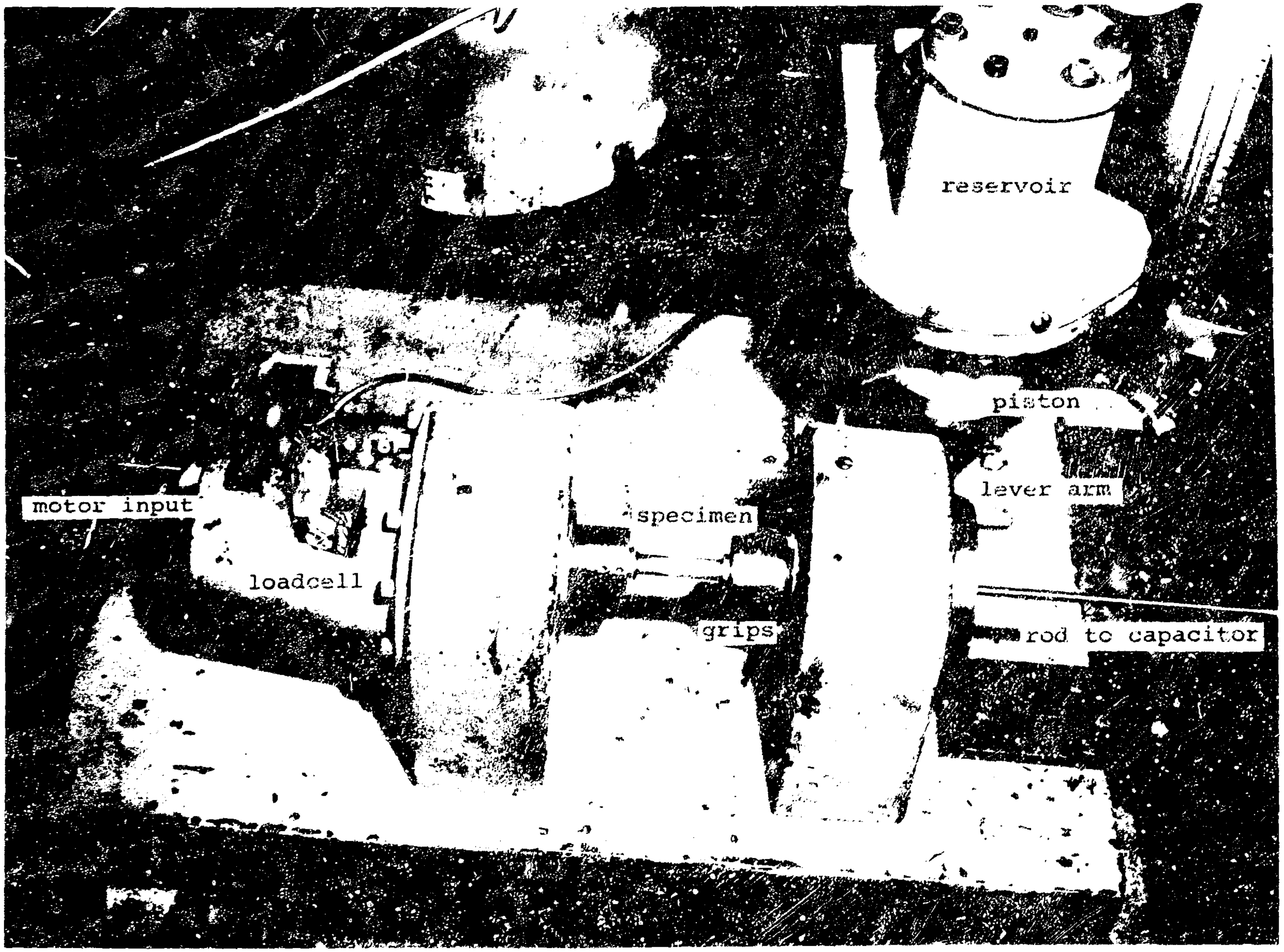

Fig. 1. Torsion Impact Machine with Specimen in Place

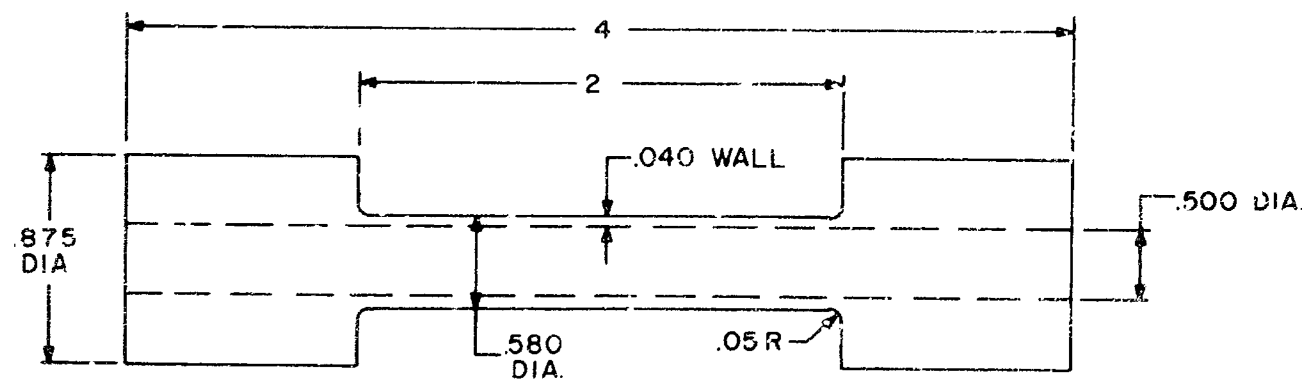

Fig. 2. Aluminum Torsion Specimen

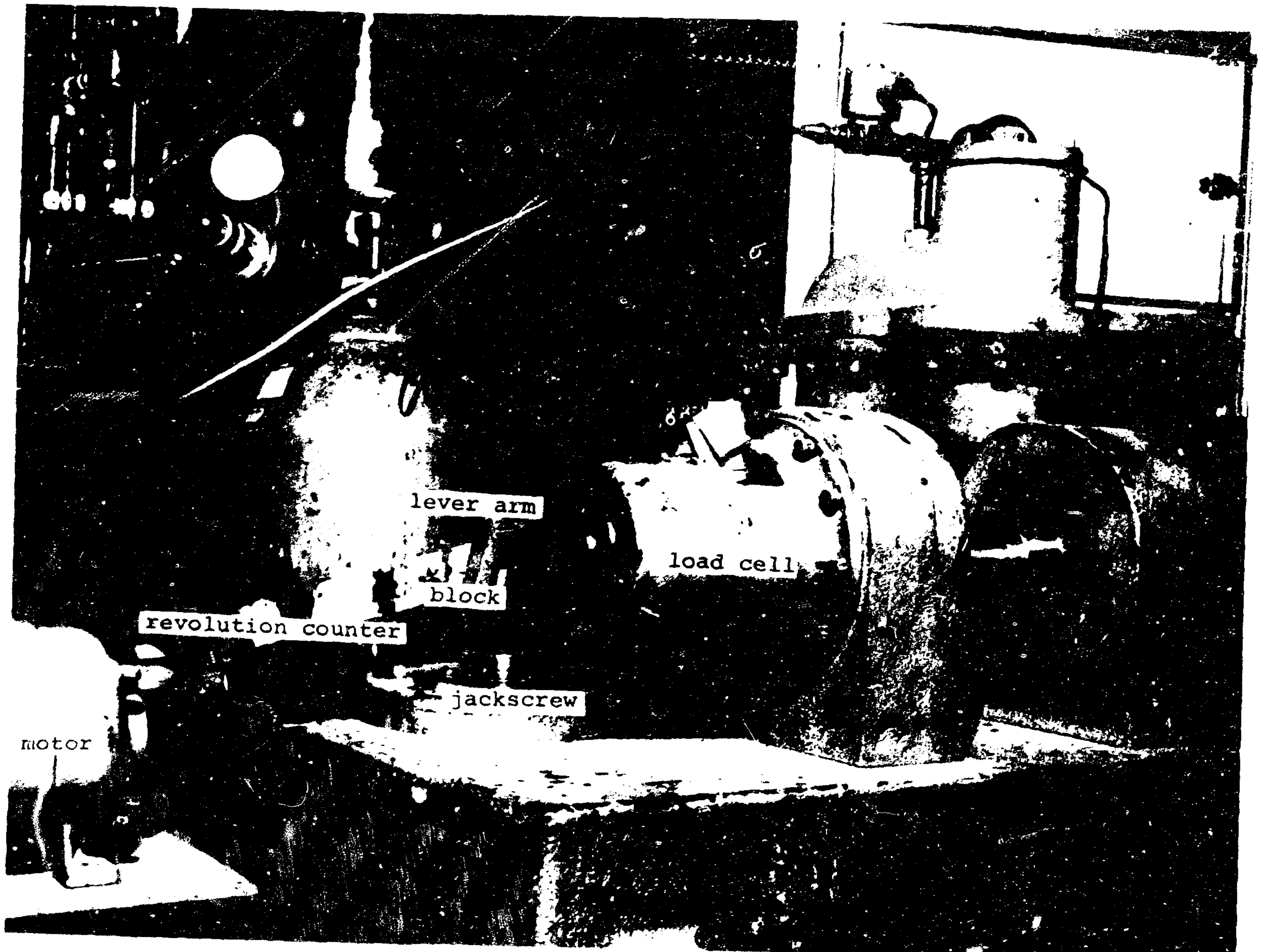

Fig. 3. Static Loading End of Machine

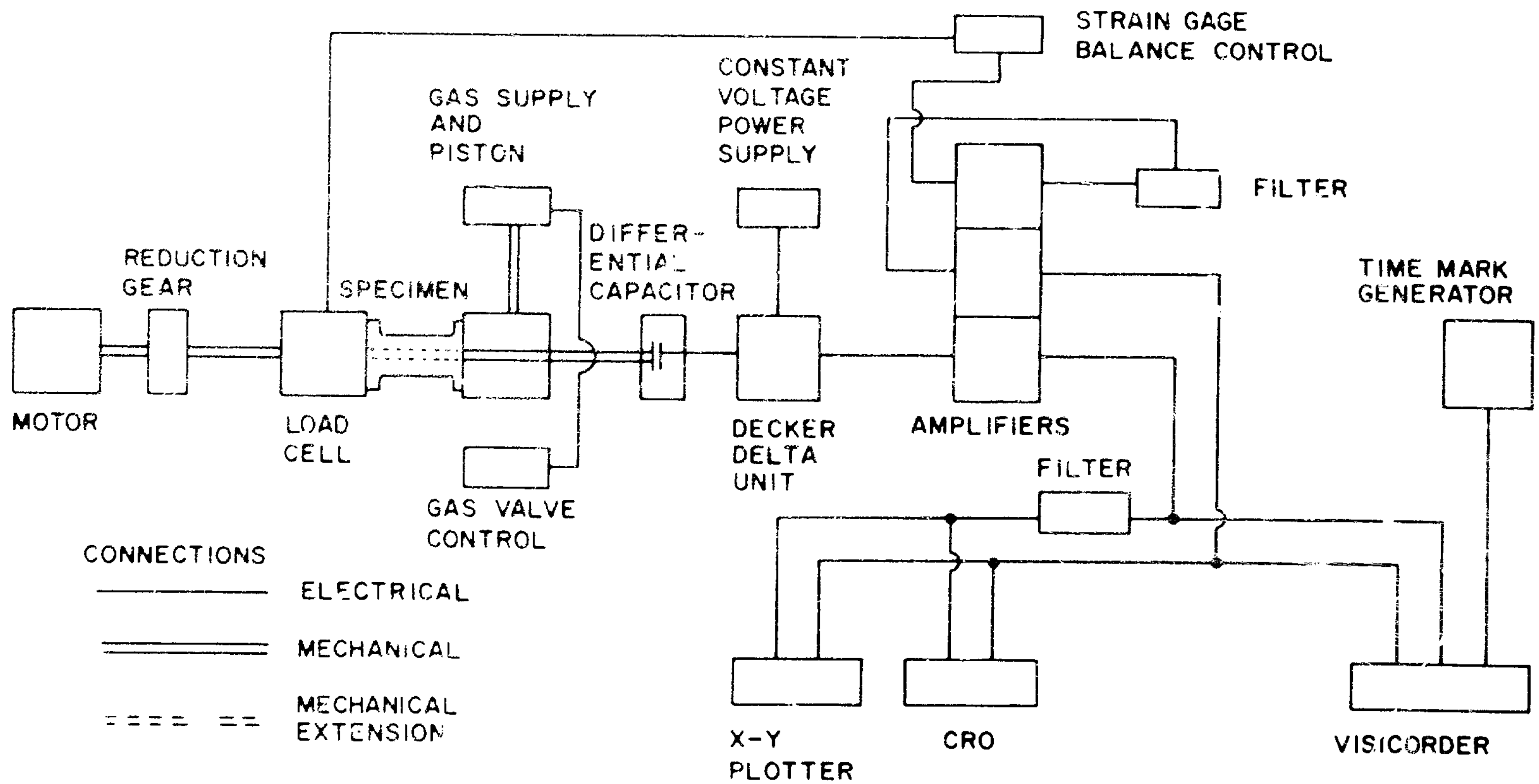

Fig. 4. Schematic of Equipm nt and Instrumentation

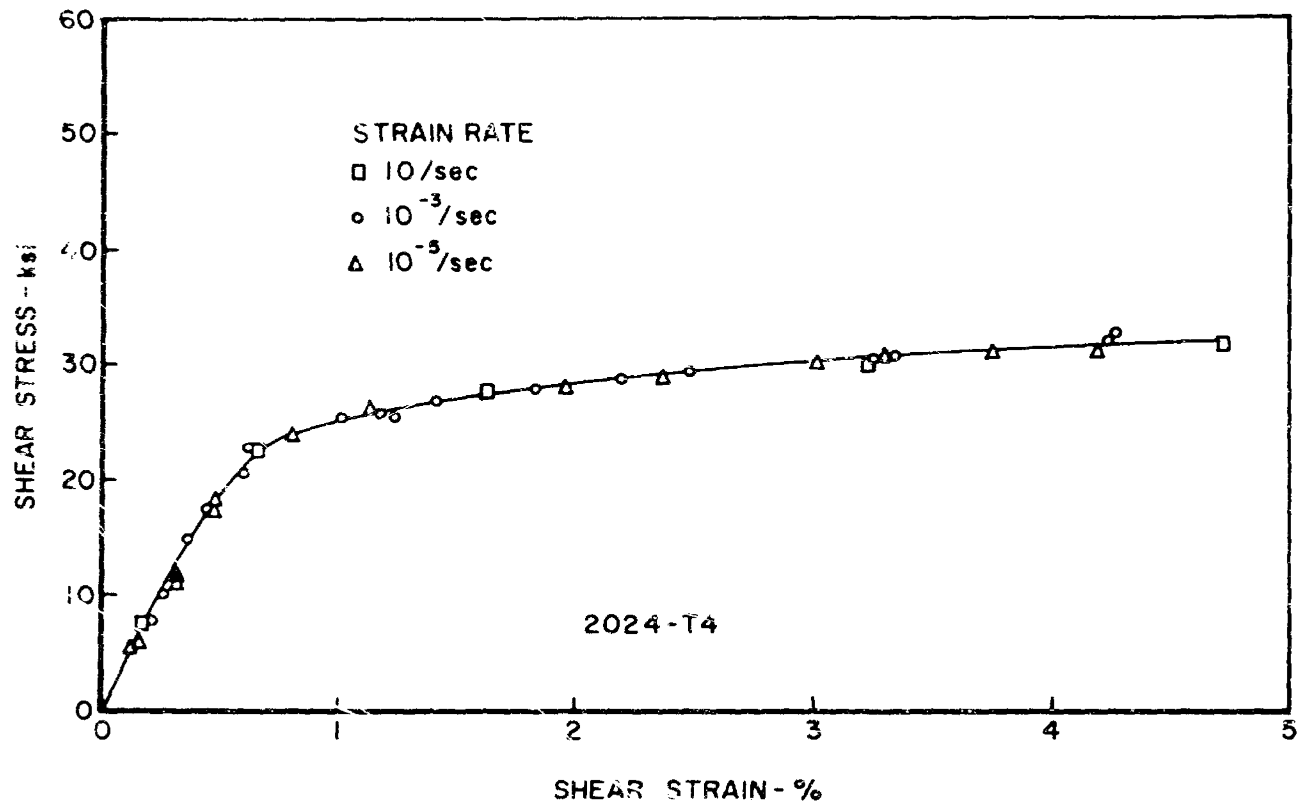

Fig. 5. Stress-Strain Curves for 2024-T4 Aluminum in Torsion

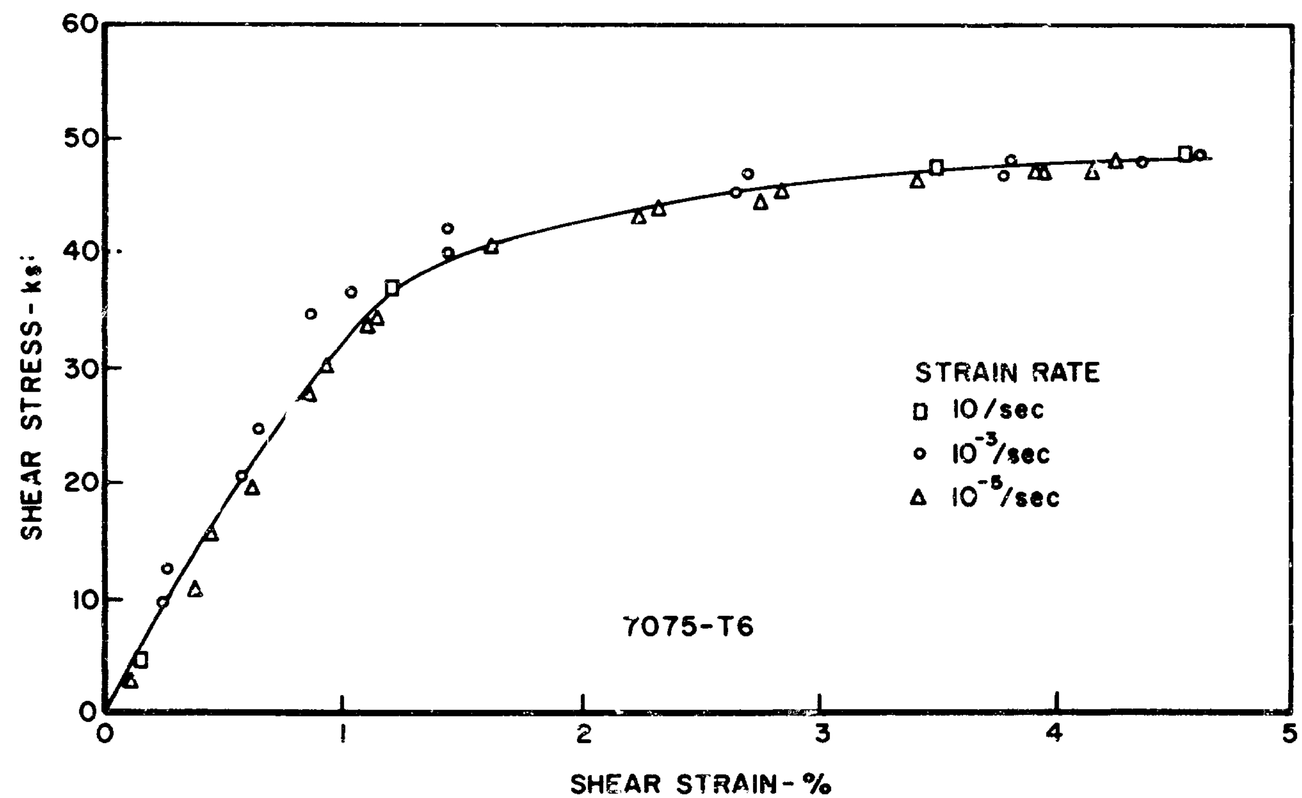

Fig. 6. Stress-Strain Curves for 7075-T6 Aluminum in Torsion

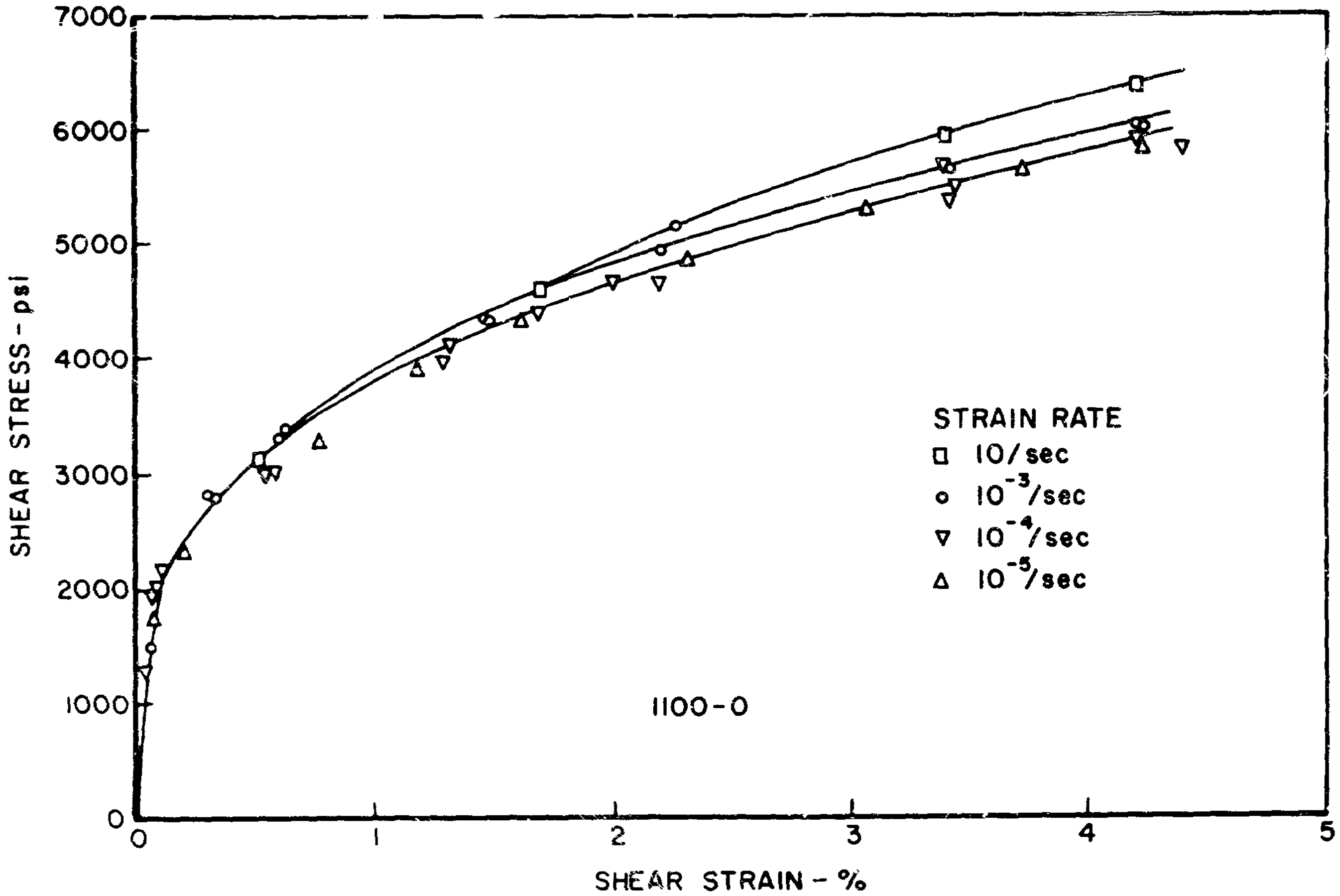

Fig. 7. Stress-Strain Curves for 1100-0 Aluminum in Torsion

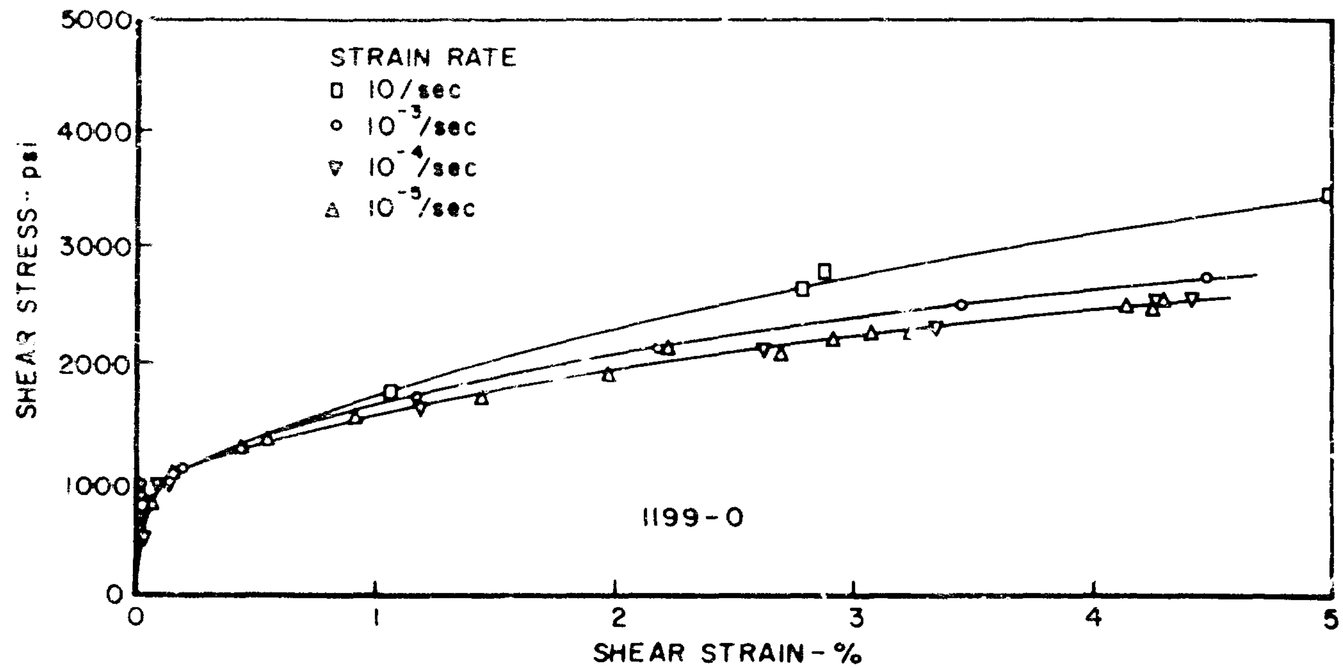

Fig. 8. Stress-Strain Curves for 1199-0 Aluminum in Torsion

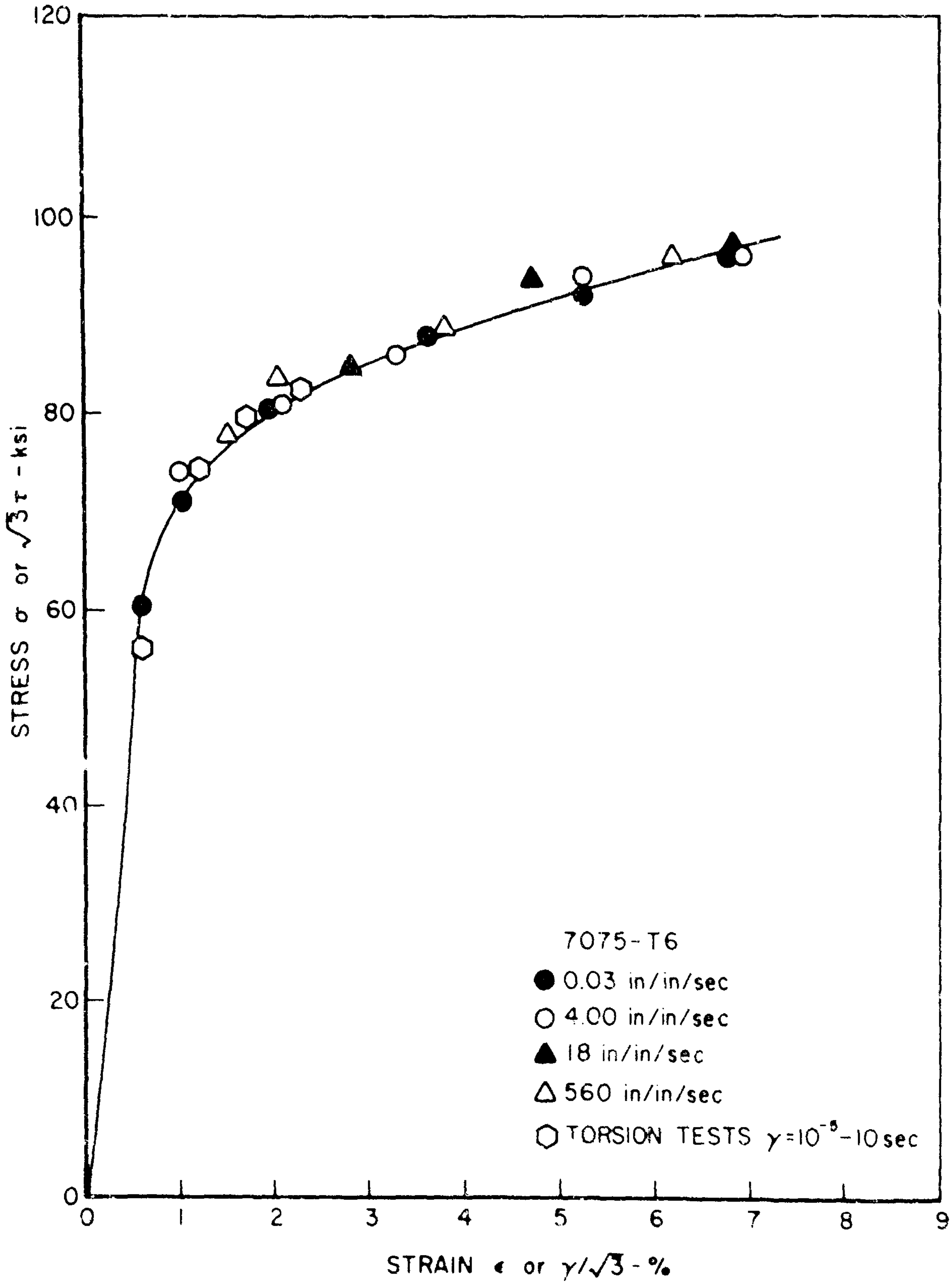

Fig. 9. Composite Stress-Strain Curve for 7075-T6 Aluminum (from Ref. 13)

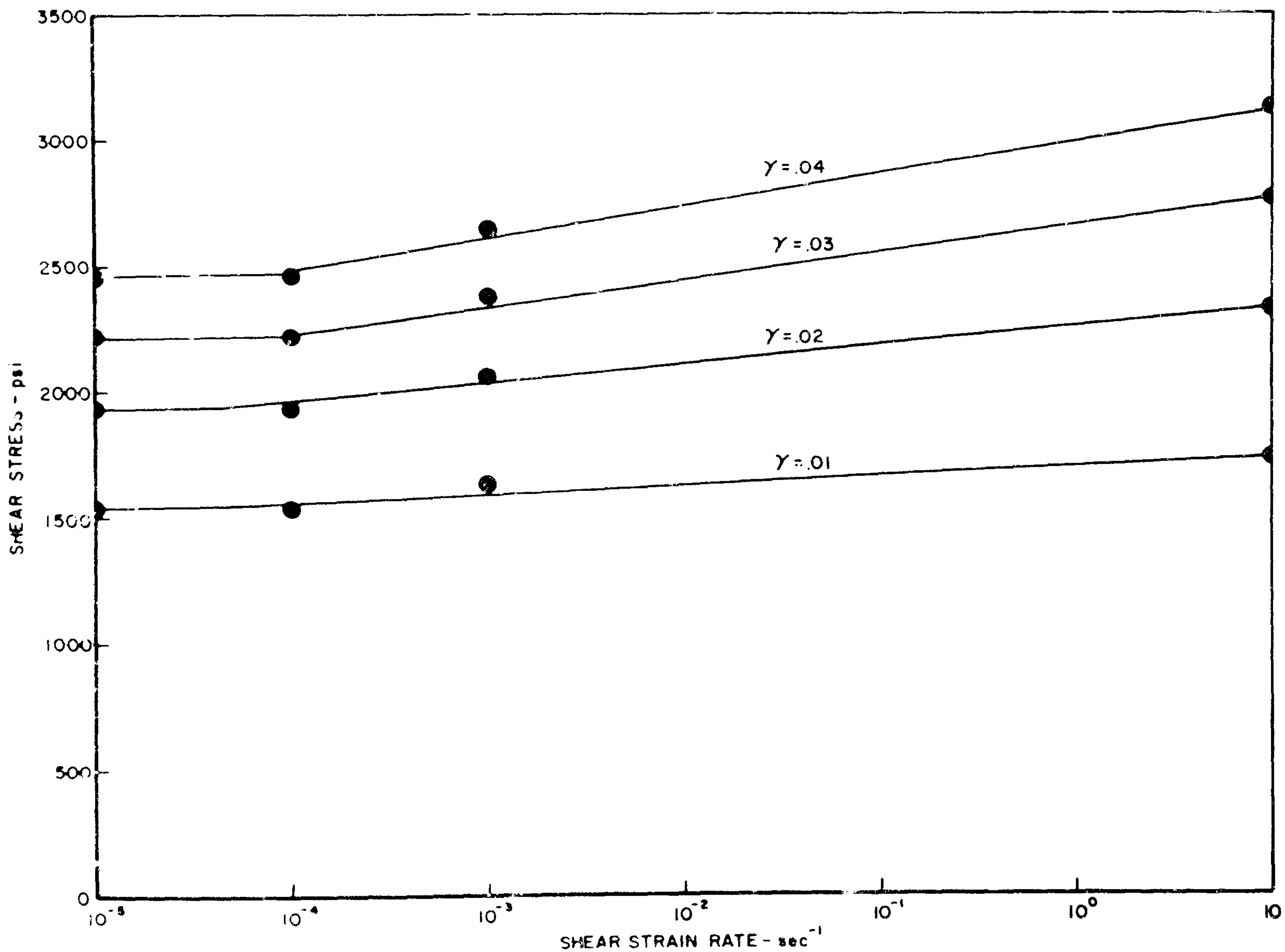

Fig. 10. Strain-Rate Dependence of Flow Stress in 1199-0 Aluminum

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13. ABSTRACT

A machine for testing hollow cylindrical specimens in torsion at shear strain rates up to 10/sec is described. A differential capacitor is incorporated in the circuitry to produce a voltage signal proportional to angle of twist of the specimen. Experimental results are presented for four aluminums in shear over a range in strain rates from 10^{-5} to 10/sec. The data show no strain-rate sensitivity in 7075-T6 and 2024-T4 aluminum and only slight rate sensitivity in 1100-0 and 1199-0 aluminum. Comparisons with results of other investigators show good agreement.

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